Top-philic particles, from theory to LHC searches

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Outline

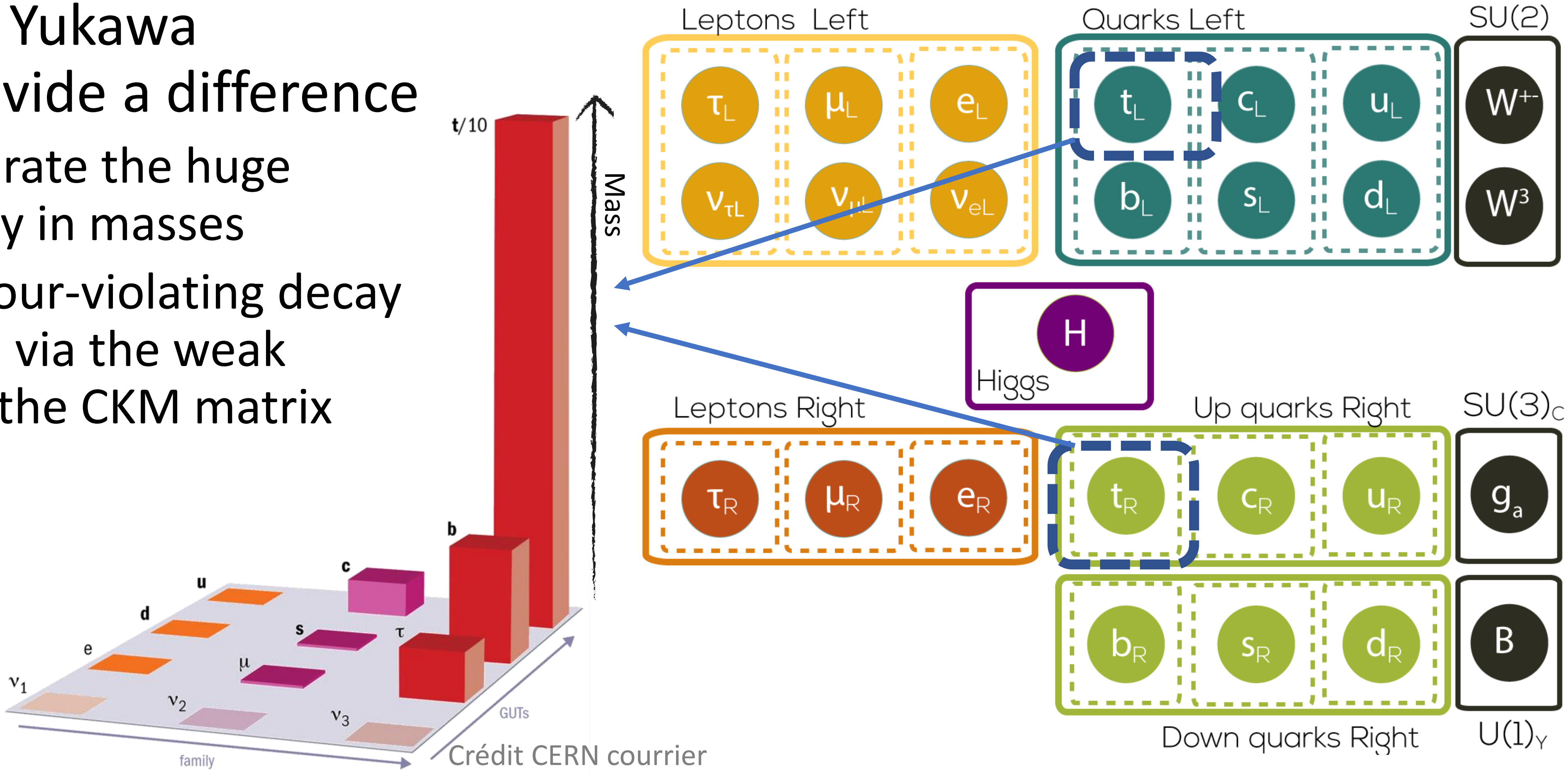
New physics models and top-philic particles

Searching for top-philic particles: EFT and simplified models in 4-top signatures

In practice: recasted limits and future directions

Flavour in the Standard Model (under 1 minute)

- SM fermions come in 3 generations, fully identical from the gauge point of view
- « Only » the Yukawa coupling provide a difference
  - →They generate the huge discrepancy in masses
  - →Allow flavour-violating decay to proceed via the weak current to the CKM matrix



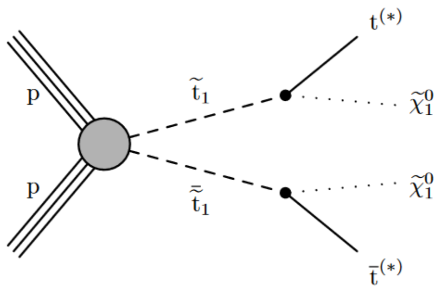
Crédit CERN courrier

New physics and top quark

- LHC is a top-quark factory with expectedly a very rich top-quark program unfolding…

- Top quark partners have been long looked after at LHC, motivated by SUSY and composite models

  → Loosely characterised as sharing (most) of the top quantum numbers and decaying to a large extent to a top quark and another particle



- In this talk, we will instead look at another class of particles, ones which do not have EW couplings at tree level, but instead a dominant interaction of the form $X\bar{t}t$

  → Thus X is a boson which decays mostly into a pair of top quarks

  → Production cannot rely on EW gauge boson or valence quarks in proton

Top-philic NP theories: the origin

- Why would a New Physics (NP) boson prefers the top quarks over its lighter siblings ?

→ This question has of course everything to do with why does the top quark is actually the heaviest one …

Because the quark mass enters into the coupling (e.g. SU(2) breaking required)

N=2 SUSY constructions (sgluon)

Generic ALP models

Because the top quark is made (partially) of NP

Partial top compositeness

Because the NP helps in generating the top quark mass

Extended Higgs sectors

Dark Higgs models (ie new singlet scalar)

Because it is a third generation quark

Flavour constructions

(Can generate top-philic vectors, leptoquarks, etc…)

Flavourful gauge groups

NP prefers the top quark because its a third generation fermion

- Unification of the SM gauge groups may proceed at the same time as the appearance of new interactions between flavour Eg. Hep-ph/9602390, or more recent works 1901.10480 , 2303.01520

  → For instance, split the SM gauge groups into generation dependent sub-group

$$SU(3)_c \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_c^{[1-2]} \times SU(3)_c^{[3]} \times SU(2)_L \times U(1)_Y$$

Early examples motivated by technicolor in the 90s, -- Hill 1994 for instance

  → Lead for instance to "Coloron" states $V_8^{\mu,a}$, behaving as third generation-specific heavy gluon (as well as many other pheno consequences)

- Horizontal "flavour" groups may also favour the heavy generations over the light ones

- However, it does not really lead to a "top-philic" scenario as typically all third generation – including bottom quark or tau – participates

Extended Higgs sector

NP prefers the top quark because it participated in giving it its mass

- The large top mass implies large Yukawa couplings
  - → Very important in extended Higgs sector searches, as the coupling to top quark can be expected to be sizeable
  - → In 2HDM, up to factors from the mixing, the couplings arise proportional to the quark masses

$$\mathcal{L}_{\text{Yukawa}}^{\text{2HDM}} = - \sum_{f=u,d,\ell} \boxed{\frac{m_f}{v}} \left(\xi_h^f \bar{f} f h + \xi_H^f \bar{f} f H - i \xi_A^f \bar{f} \gamma_5 f A \right)$$

	Type I	Type II	Lepton-specific
ξ_H^u	$\sin\alpha / \sin\beta$	$\sin\alpha / \sin\beta$	$\sin\alpha / \sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$

$$\tan\beta = \frac{v_2}{v_1} \qquad H^{\text{SM}} = h \sin(\alpha - \beta) - H \cos(\alpha - \beta)$$

See, e.g. 2202.02333 for a recent work

- The pseudo-scalar is a good top-philic candidate, as it does not have also a tree-level coupling to gauge bosons in CP-preserving case

Corresponding simplified model

$$\boxed{\mathcal{L}_{S_1} \supset \frac{1}{2} \partial_\mu S_1 \partial^\mu S_1 - \frac{1}{2} m_{S_1}^2 S_1^2 + \bar{t} \left[y_{1S} + y_{1P} i \gamma^5 \right] S_1 \, t}$$

Composite constructions

NP prefers the top quark because it is partially NP itself

- Partial compositeness scenarios

See e,g. 1507.02283, 1610.06591, etc…

  → While the Higgs boson is a composite state, the generation of Yukawa couplings is challenging

  → Many pNGB are generated, possibly colored (octet, sextet, etc…)

  → Also presence of vector "meson" composite states

The color representation of the pNGB depends on the details of the composite models …

- The top mass is obtained by mixing a fundamental quark field with new composite baryonic states, thus it inherits a preferential coupling to the pNGB

Corresponding simplified model

$$\mathcal{L}_{S_8} \supset \frac{1}{2} D_\mu S_8^a D^\mu S_{8a} - \frac{1}{2} m_{S_8}^2 S_8^a S_{8a} + \bar{t}\left[y_{8S} + y_{8P} i\gamma^5\right] S_8\, t$$

$$\mathcal{L}_{V_8} \supset -\frac{1}{4} V_8{}^{\mu\nu} V_{8\mu\nu} - \frac{1}{2} m_{V_8}^2 V_8{}^{\mu} V_{8\mu} + \bar{t}\gamma_\mu \left[g_{8L} P_L + g_{8R} P_R\right] V_8{}^{\mu}\, t$$

+ also sextet and singlet states …

Broad formalism, not very predictive from the top-down approach

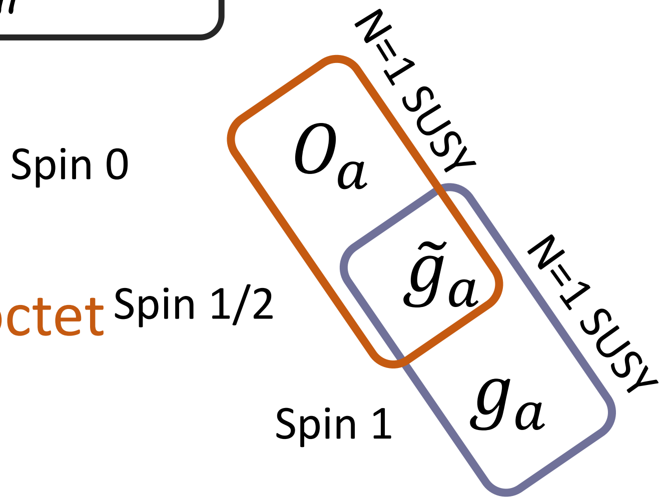
SUSY constructions

NP prefers the top quark because it is the heaviest of all

- Dirac Supersymmetric model

See, e.g. 2107.13565 for a recent work

→ makes gauginos Dirac fermions instead of Majorana, which contains half of the gluino degrees of freedom and a new, color octet complex scalar



- Main interest: use D-term SUSY-breaking approach. The corresponding Dirac mass terms for gauginos $L \supset -m_3 \, \bar{\tilde{g}}_a \, \tilde{g}_a$ are “supersoft”

→ They only trigger a finite radiative corrections (not logarithmic ones)

→ Leave stops as the main source of tuning and relax constraints on gluinos

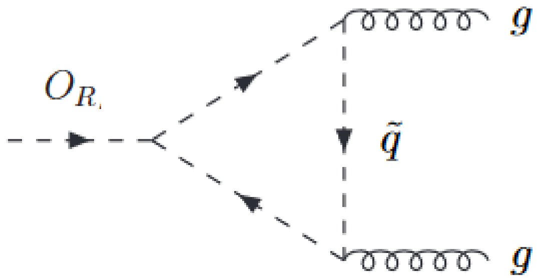
$$O = \frac{O_R + \boxed{iO_I}}{\sqrt{2}} \longrightarrow$$

The pseudo-scalar octet O_I only couples to gluinos at tree-level

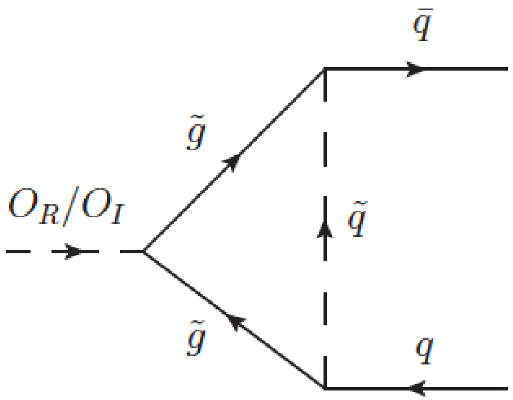
The cost is that we need to add new scalar fields in the adjoint of the SM gauge groups

Supersymmetric constructions 2

- How does top-philia arises for the scalar octet?
  - → At tree-level, it *only* couples to the SM gluons via its covariant derivatives $D_\mu O_I D^\mu O_I$, allows for pair-production, but not decay…
  - → The pseudo-scalar does not couples to squarks at tree-level, thus there is no loop-induced gluon coupling for O_I



$g_{O_I gg} \propto 0$



$g_{Oqq} \propto m_q$

required by chirality flip + the fact that all couplings in the loop are in g_s

D-term origin → only the real part couples to squarks

Corresponding simplified model

$$\mathcal{L}_{S_8} \supset \boxed{\frac{1}{2} D_\mu S_8^a D^\mu S_{8a}} - \frac{1}{2} m_{S_8}^2 S_8^a S_{8a} + \bar{t}\left[y_{8S} + y_{8P} i\gamma^5\right] S_8\, t$$

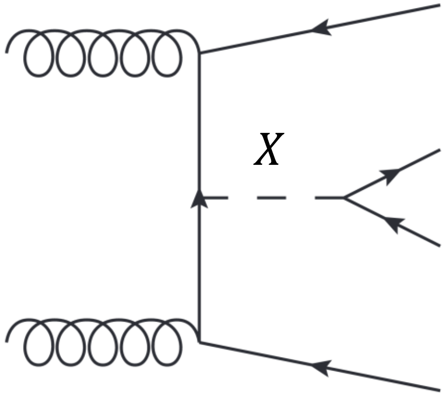
Include direct QCD interactions

Searching for top-philic particles

4-top final states, EFT vs simplified models

How to look for a heavy top-philic state ?

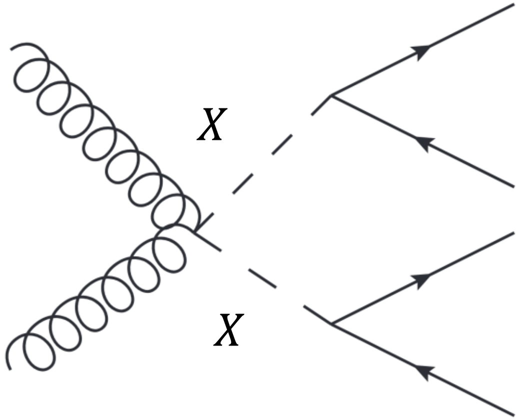
- The key requirement is that is decays mostly to tops, so we have the main requirements that couplings to g, q… are much smaller than $y_{X,t}$



Final state: $ttX, X \to tt$

$\sigma \propto y_{Xt}^2$

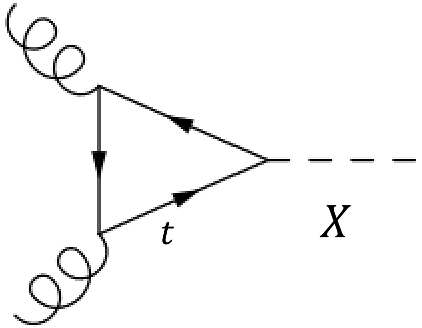
But need energetic gluons …



Final state: $XX, X \to tt$

$\sigma \propto g_s^4$

Works only if the top-philic state is an octet

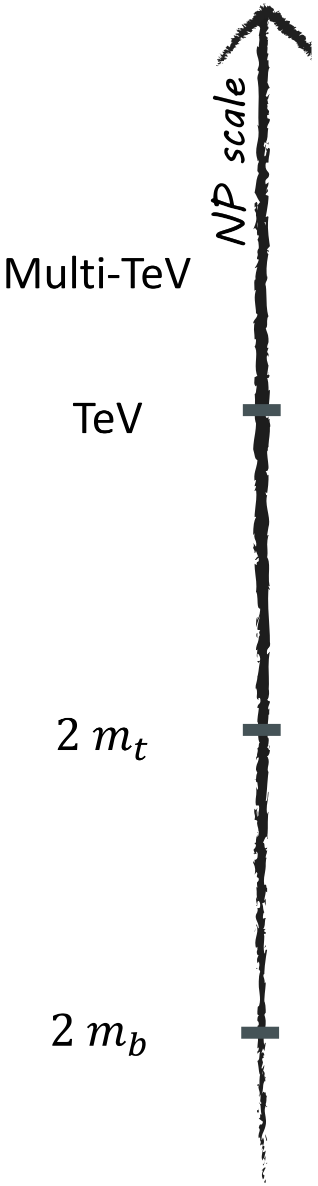


Final state: X

$\sigma \propto \frac{g_s^4 y_{Xt}^2}{\pi^4}$

Loop-induced, but no PDF suppression + only one X to produce

From resonant searches to EFT



- The NP is completely decoupled, the SMEFT approach is relevant

$$pp \to \bar{t}t\bar{t}t$$

- The “high-pT” region, one or two NP particles produced on-shell

$$pp \to \bar{t}tX, XX\ , \qquad X \to t\bar{t}$$

When should we move from one description to the other ?

- Resonance easily produced, but decay with little pT

$$pp \to \bar{t}tX, XX\ , \qquad X \to t\bar{t}$$

Large signal rate / Large background region

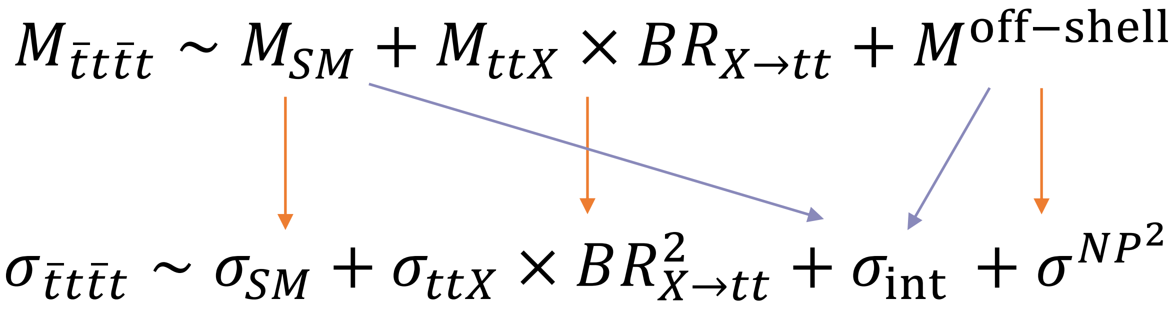
- Resonance easily produced, but decay cannot proceed in tops

$$pp \to \bar{t}tX^* \to \bar{t}t\bar{t}t$$

But also $\bar{t}t\ (\bar{b}b), \bar{t}t\ (\bar{\tau}\tau)$, *etc …*

Cross-section estimates

- The amplitude for the $pp \to \bar{t}t\,\bar{t}t$ with a NP simplified model can be (artificially) decomposed in 3 main pieces

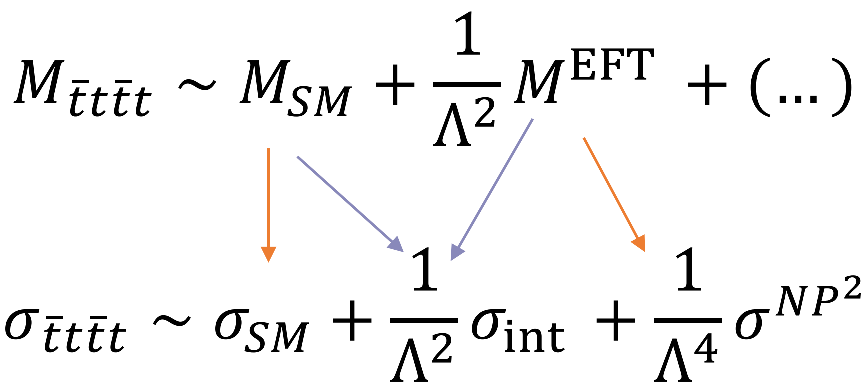


$$M_{\bar{t}t\bar{t}t} \sim M_{SM} + M_{ttX} \times BR_{X\to tt} + M^{\text{off−shell}}$$

$$\sigma_{\bar{t}t\bar{t}t} \sim \sigma_{SM} + \sigma_{ttX} \times BR^2_{X\to tt} + \sigma_{\text{int}} + \sigma^{NP^2}$$

Contrary to the ”usual” case, we just started to measure σ_{SM}…

- For the EFT, the on-shell piece is assumed to be subdominant



$$M_{\bar{t}t\bar{t}t} \sim M_{SM} + \frac{1}{\Lambda^2} M^{\text{EFT}} + (\dots)$$

$$\sigma_{\bar{t}t\bar{t}t} \sim \sigma_{SM} + \frac{1}{\Lambda^2}\sigma_{\text{int}} + \frac{1}{\Lambda^4}\sigma^{NP^2}$$

Given the current sensitivity, LHC (and HL-LHC) are in a regime with:

$$\sigma_{SM} \sim \frac{1}{\Lambda^4}\sigma^{NP^2} \gtrsim \frac{1}{\Lambda^2}\sigma_{\text{int}}$$

A minimal EFT basis

- Simplified models often include EWSB

  → Using $SU(3)_c \times U(1)_{em}$ basis is important and leads to additional operators

- Typical SMEFT approach is redundant for top-only operators

  → No need to keep track of b-quark

EW-breaking part (P-conserving)

$$\mathcal{O}^1_S = \bar{t}t\;\bar{t}t$$

$$\mathcal{O}^8_S = \bar{t}T^A t\;\bar{t}T_A t$$

EW-preserving part

$$\mathcal{O}^1_{RR} = \bar{t}_R\gamma^\mu t_R\;\bar{t}_R\gamma_\mu t_R$$

$$\mathcal{O}^1_{LL} = \bar{t}_L\gamma^\mu t_L\;\bar{t}_L\gamma_\mu t_L$$

$$\mathcal{O}^1_{LR} = \bar{t}_L\gamma^\mu t_L\;\bar{t}_R\gamma_\mu t_R$$

$$\mathcal{O}^8_{LR} = \bar{t}_L T^a\gamma^\mu t_L\;\bar{t}_R T_a\gamma_\mu t_R$$

Also two further P-breaking operators…

$$O_{tt} = (\bar{t}_R\gamma_\mu t_R)^2$$

$$O_{tq} = (\bar{t}_R\gamma_\mu t_R)(\bar{q}_L\gamma^\mu q_L)$$

$$O^{(8)}_{tq} = \left(\bar{t}_R\gamma_\mu t^A t_R\right)\left(\bar{q}_L\gamma^\mu t^A q_L\right)$$

$$O_{qq} = (\bar{q}_L\gamma_\mu q_L)^2$$

$$O^{(8)}_{qq} = \left(\bar{q}_L\gamma_\mu t^A q_L\right)^2$$

Four-top operators used in 2010.05915

$$O^{(8)}_{qq} \sim O_{qq}/3$$

Importance of EW interference effect (LO)

- Interferences become important for CS around the fb, and EW-contributions are dominant!

→ Similar to the full SM result where $\alpha_S^2\alpha_{EW}^2$ terms were found much larger than expected

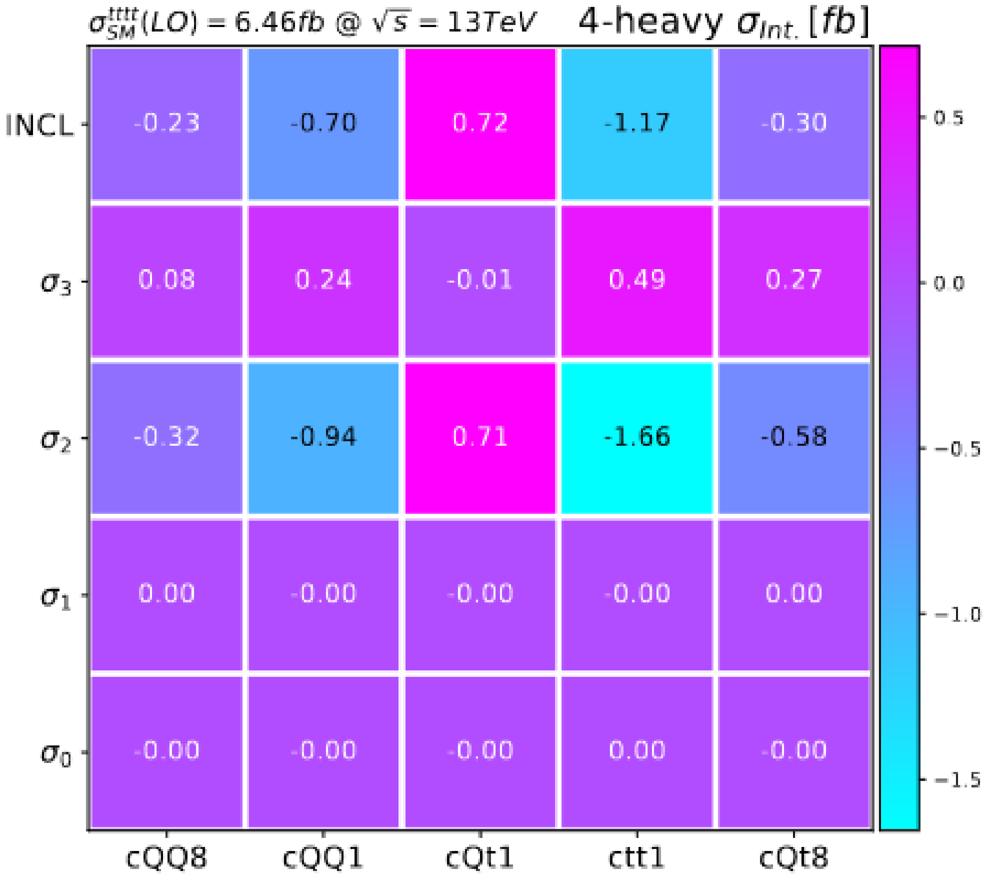
Frederix, Pagani, Zaro 1711.02116

→ For the "heavy quark" operators, $\alpha_S^2\alpha_{EW}^1$ tend to dominate the interference contribution

$$\sigma_{incl}^{int} \sim \underset{\alpha_S^3}{\sigma_3} + \underset{\alpha_S^2\alpha_{EW}^1}{\sigma_2} + \underset{\alpha_S^1\alpha_{EW}^2}{\sigma_1} + \underset{\alpha_{EW}^3}{\sigma_0}$$

For the $c/\Lambda \sim 1$*, the NP² terms are of the same order as the interferences*

Aoude et al. 2208.04962



	cQQ8	cQQ1	cQt1	ctt1	cQt8
INCL	-0.23	-0.70	0.72	-1.17	-0.30
σ_3	0.08	0.24	-0.01	0.49	0.27
σ_2	-0.32	-0.94	0.71	-1.66	-0.58
σ_1	0.00	-0.00	-0.00	-0.00	0.00
σ_0	-0.00	-0.00	-0.00	0.00	-0.00

- Conclusion: always include EW interference in your simulations

See also Ježo and Kraus (2110.15159)

Simplified models

- We consider singlet top-philic particles…

Include EWSB contributions

$$\mathcal{L}_{S_1} \supset \frac{1}{2}\partial_\mu S_1 \partial^\mu S_1 - \frac{1}{2} m_{S_1}^2 S_1^2 + \bar{t}\left[y_{1S} + y_{1P} i\gamma^5\right] S_1\, t$$

→ contained for instance in 2HDM type-I or type-II

$$\mathcal{L}_{V_1} \supset -\frac{1}{4} {V_1}^{\mu\nu} V_{1\mu\nu} - \frac{1}{2} m_{V_1}^2 {V_1}^{\mu} V_{1\mu} + \bar{t}\gamma_\mu \left[g_{1L} P_L + g_{1R} P_R\right] {V_1}^{\mu}\, t$$

→ Via mixing with new VL quarks, etc…

- And color octets top-philic particles

$$\mathcal{L}_{S_8} \supset \boxed{\frac{1}{2} D_\mu S_8^a D^\mu S_{8a}} - \frac{1}{2} m_{S_8}^2 S_8^a S_{8a} + \bar{t}\left[y_{8S} + y_{8P} i\gamma^5\right] S_8\, t$$

→ Composite models, N=2 SUSY …

$$\mathcal{L}_{V_8} \supset \boxed{-\frac{1}{4} {V_8}^{\mu\nu} V_{8\mu\nu} -} \frac{1}{2} m_{V_8}^2 {V_8}^{\mu} V_{8\mu} + \bar{t}\gamma_\mu \left[g_{8L} P_L + g_{8R} P_R\right] {V_8}^{\mu}\, t$$

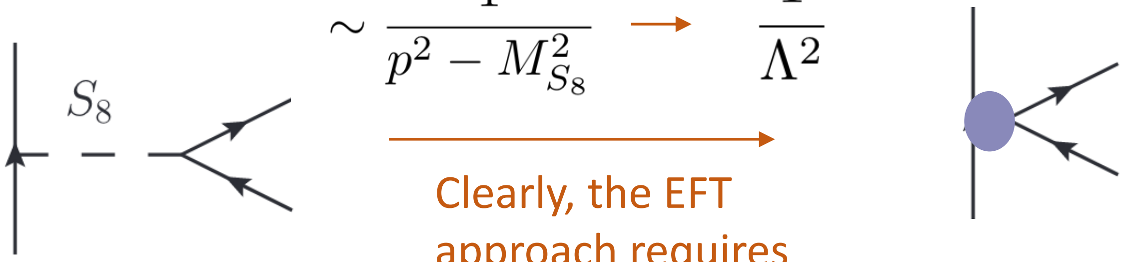
→ Composite models…

Include direct QCD interactions

Simplified models matching (1.0.1)

- Integrating out the to match EFT and simplified models (particularly easy in this case)

  → Followed by Fierz transformations to fall back to our minimal basis …



$$\sim \frac{1}{p^2 - M_{S_8}^2} \rightarrow \frac{1}{\Lambda^2}$$

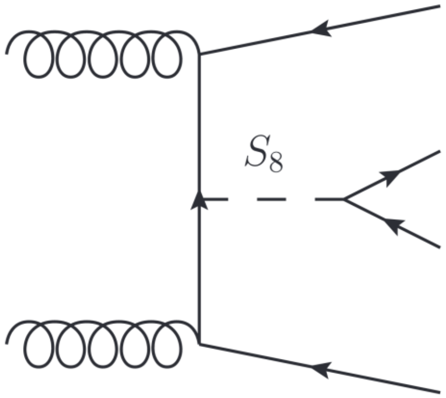
Clearly, the EFT approach requires heavy top-philic mediator

- The EFT basis is compact enough that, e.g. pseudo-scalar top-philic particles do not need a dedicated operator

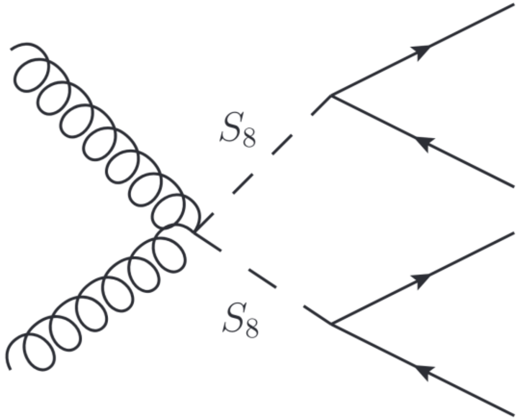
	$\mathcal{O}_S^1$	$\mathcal{O}_S^8$	$\mathcal{O}_{LL}^1$	$\mathcal{O}_{RR}^1$	$\mathcal{O}_{LR}^1$	$\mathcal{O}_{LR}^8$
S_1	$\frac{y_{1S}^2}{2M_{S_1}^2}$	/	/	/	/	/
$\tilde{S}_1$	$-\frac{y_{1P}^2}{2M_{\tilde{S}_1}^2}$	/	/	/	$-\frac{y_{1P}^2}{3M_{\tilde{S}_1}^2}$	$-2\frac{y_{1P}^2}{M_{\tilde{S}_1}^2}$
V_8	/	/	$-\frac{g_{1L}^2}{6M_{V_8}^2}$	$-\frac{g_{1R}^2}{6M_{V_8}^2}$	/	$-\frac{g_{8L}g_{8R}}{M_{V_8}^2}$

EFT viability

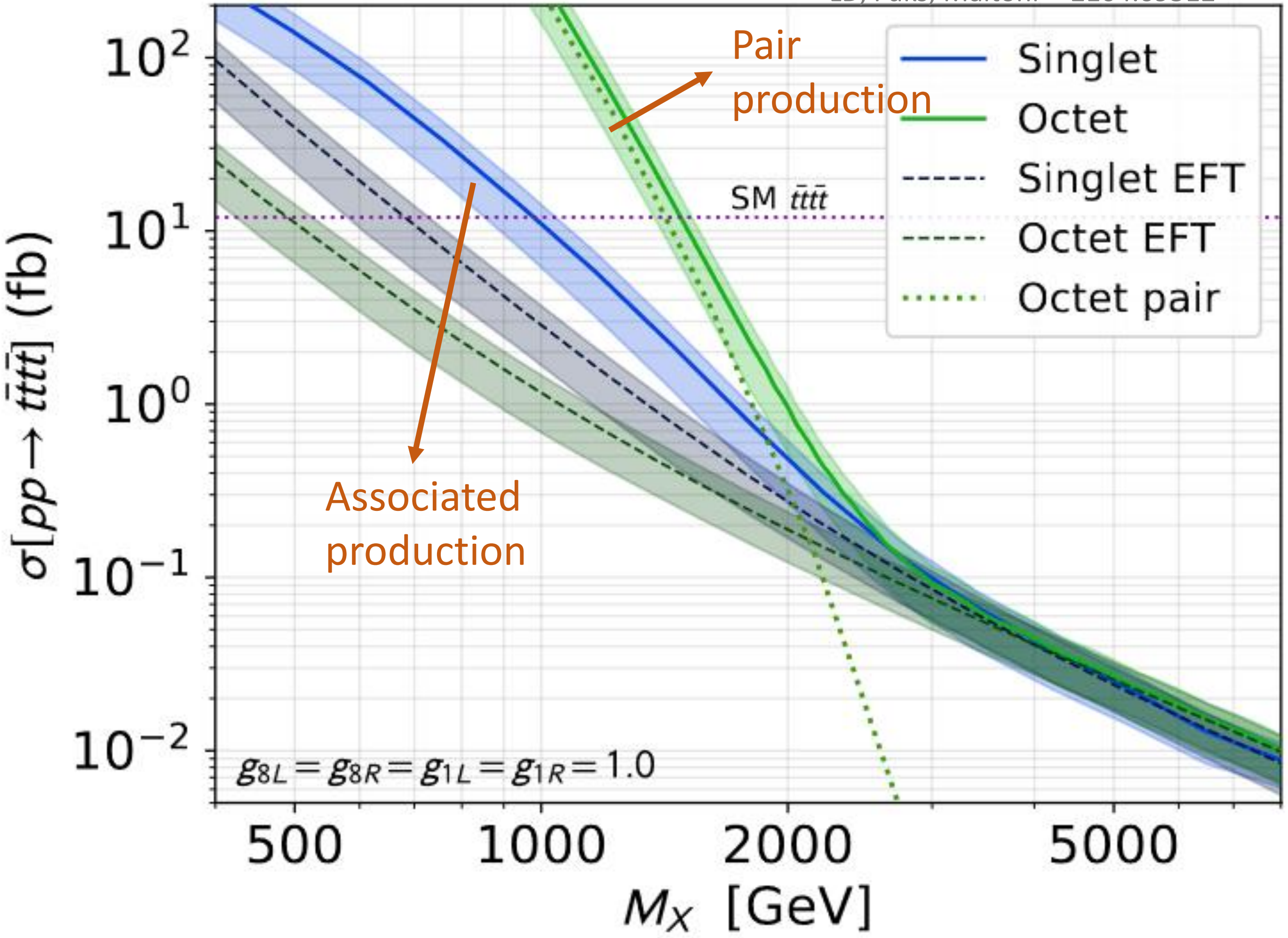
- The projected constraints, even at HL-LHC points to g/Λ at the TeV level
  - → In the low mass regime, on-shell production dominates
  - → Either in associated



  - → Or if available, by pair



LD, Fuks, Maltoni -- 2104.09512



Summary so far and NLO

- In our UV-motivated simplified model scenarios, matching with the EFT prediction do not occur for CS accessible at LHC

  → Or need non-perturbative couplings (e.g. via composite models !)

- What happens in term of actual searches ?

  → Do current searches able to leverage the fact that NP must be typically produced on-shell to be detectable ?

- As an aside, the above is made at LO+interference, the full NLO+interference is not known for all the simplified models yet

  Frederix, Pagani, Zaro 1711.02116

  → In the SM, NLO-correction in QCD dominates are large $K_{SM} \sim 2.3$, and the same for pair production in the case of pseudo-scalar octet led to $K_{QCD} \sim 2$

  LD, Fuks, Goodsell 1805.10835

  → In the SMEFT, much smaller effects,
  Depends on the operator, typically $K_{QCD} \gtrsim 1$ Degrande et al. 2008.11743

  We will present limits varying the K-factor between 1 and 2 when not known

Finding recasted limits and future directions

The CMS four-top analysis

- Based on Run-3 with multi-lepton

  → We based ourselves on 1908.06463 with same-sign leptonic final states (the updated paper with all final states is just out, 2303.03864)

  → Both BDT and SR-based strategy based on number of jets/leptons …

  → Backgrounds include $t\bar{t}W$, $t\bar{t}Z$, non-prompt leptons etc …

N_ℓ	N_b	N_j	Region	$t\bar{t}t\bar{t}$ (SM - CMS)	$t\bar{t}t\bar{t}$ (Bkd - CMS)
2	3	6	SR5	1.61 ± 0.90	5.03 ± 0.77
2	≥ 4	≥ 5	SR8	2.08 ± 1.23	3.31 ± 0.95
≥ 3	≥ 3	4	SR12	0.56 ± 0.32	2.03 ± 0.48
≥ 3	≥ 3	5	SR13	0.66 ± 0.38	1.09 ± 0.28
≥ 3	≥ 3	≥ 6	SR14	0.76 ± 0.45	0.87 ± 0.30

CMS (17)
$\sigma_{4t}^{SM} = 16.9^{+13.8}_{-11.4}$ fb
$35.9\ \mathrm{fb}^{-1}$
(CMS 1710.10614)

CMS (19)
$\sigma_{4t}^{SM} = 12.6^{+5.8}_{-5.2}$ fb
$137\ \mathrm{fb}^{-1}$
(CMS 1908.06463)

CMS (23)
$\sigma_{4t}^{SM} = 17^{+5}_{-5}$ fb
$138\ \mathrm{fb}^{-1}$
(CMS 2303.03864)

- Since SM-driven, we need a full recast to get reliable NP bound

Recasting setup

- Simple recasting chain:
  - FeynRules

[Christensen & Duhr (CPC ’09); Alloul et al.(CPC’14) Degrande (CPC’16)]

  - MG5_aMC@NLO

Alwall et al. (JHEP’14)

  - PYTHIA 8

Sjostrand et al. (CPC’15)

  - MadAnalysis 5

[Conte et al.(CPC’12); Conte et al. (EPJC’14) Dumont et al. (EPJC ’15)]

Implement EFT and simplified models Lagrangians, e.g.

$$\mathcal{L}_{S_1} \supset \frac{1}{2}\partial_\mu S_1 \partial^\mu S_1 - \frac{1}{2} m_{S_1}^2 S_1^2 + \bar{t}\left[y_{1S} + y_{1P} i\gamma^5\right] S_1 t$$

Load UFO, generate $pp \to tttt$, including EW interferences

Decay tops inclusively t > w+ b, w+ > all al

The cross-section/signal shape depends only on the top-philic particle mass. → Scan over it

MadAnalysis 5 implementation

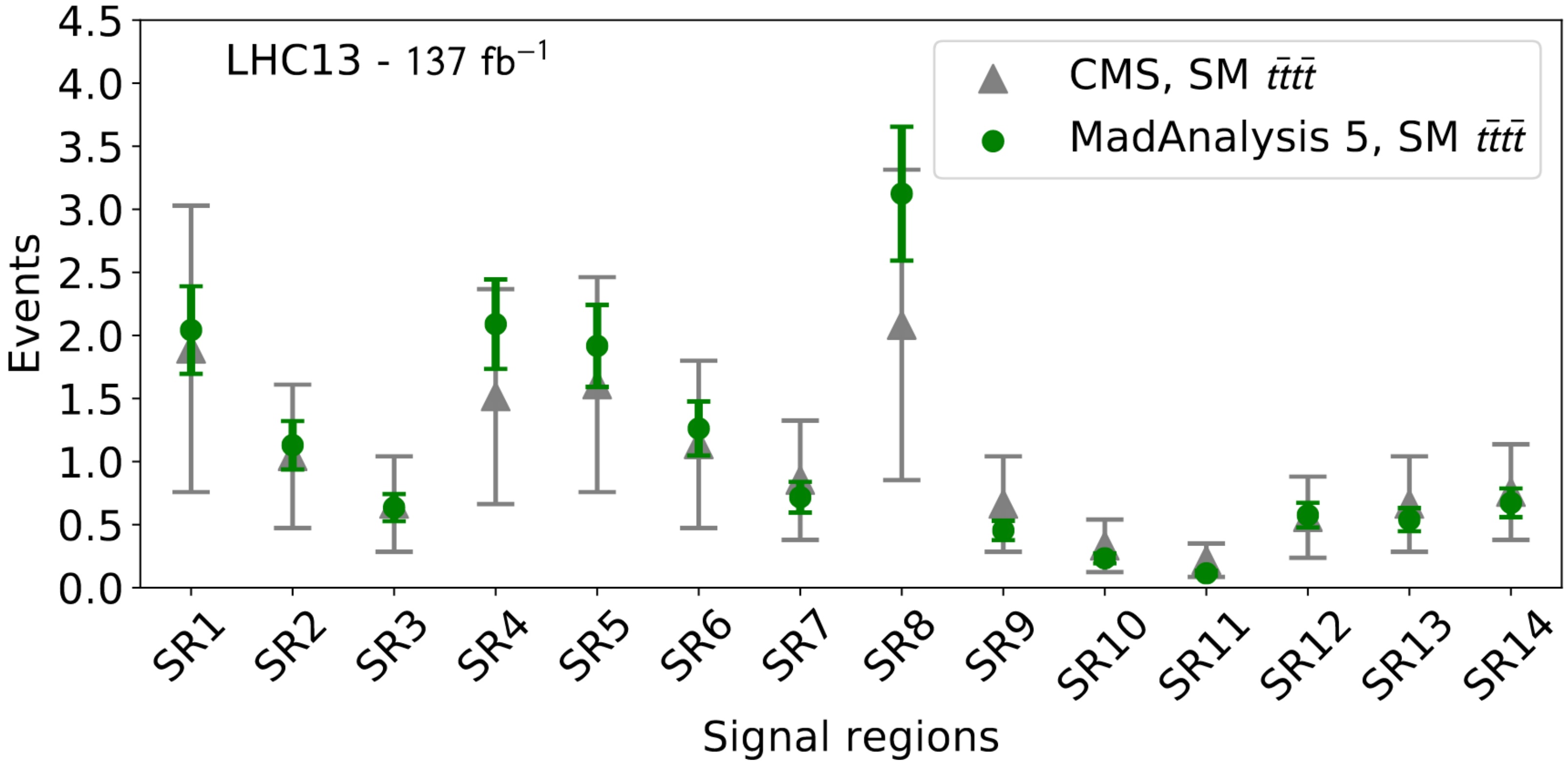
- Challenging analysis to reproduce

→ High-multiplicity final states: isolation criteria (defined back in CMS' 1605.0317)

→ Relatively strong cuts (sizeable MC dataset required), signal efficiency < 0.002

- Signal regions depend crucially on number of b-tagged jets;

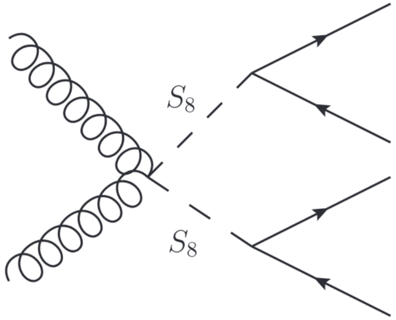
→ Reproduce the efficiency of DeepCSV algorithm, medium working point in Delphes (MA5 tune)



SM vs NP signals

- Typical NP signal use on-shell production+ decay

  → starkly different kinematics w.r.t the SM

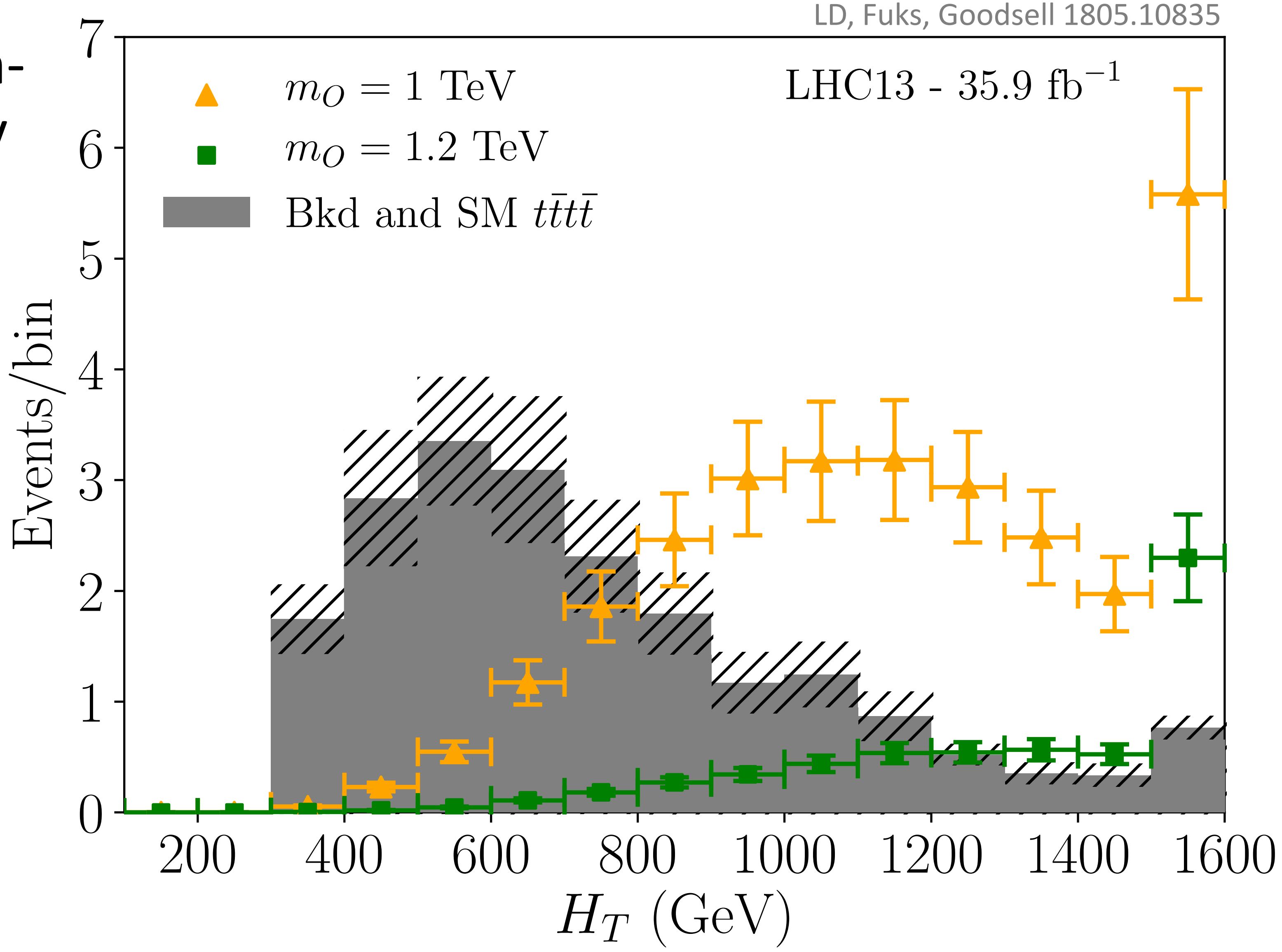


- We add a signal region with $H_T > 1.2$ TeV to the CMS search

$$N_{\text{bkd+SM}} = 6.26 \pm 1.3$$

$$N_{\text{obs}} = 9$$

LD, Fuks, Goodsell 1805.10835



Signal efficiencies

- Comparing selection cut efficiencies for both approaches

  → EFT efficiencies close to simplified models ones for CMS analysis

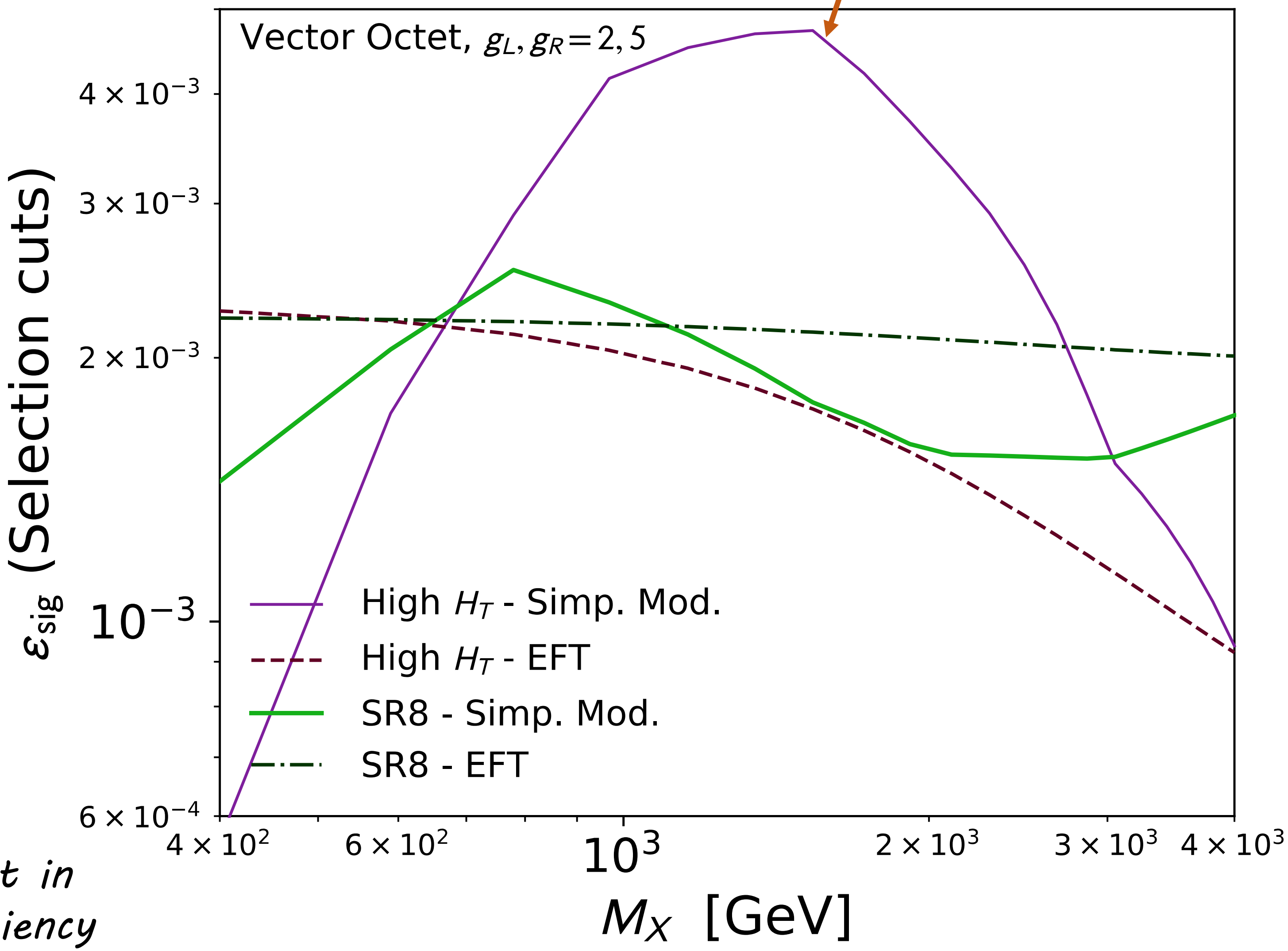
- "On-shell" effects important

  → High Ht analysis has a very good signal efficiency in the 1-3 TeV mass window

Above this range, the distribution was put in overflow in the CMS analysis, so the efficiency falls …

Large pT from octet decay

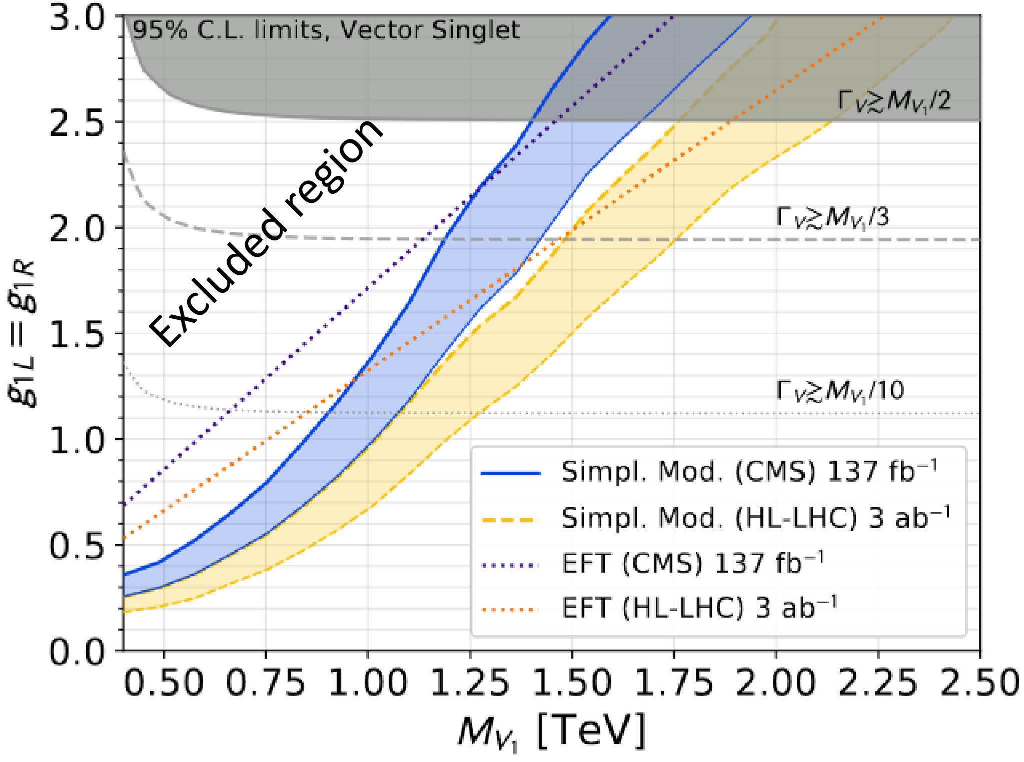
LD, Fuks, Maltoni -- 2104.09512



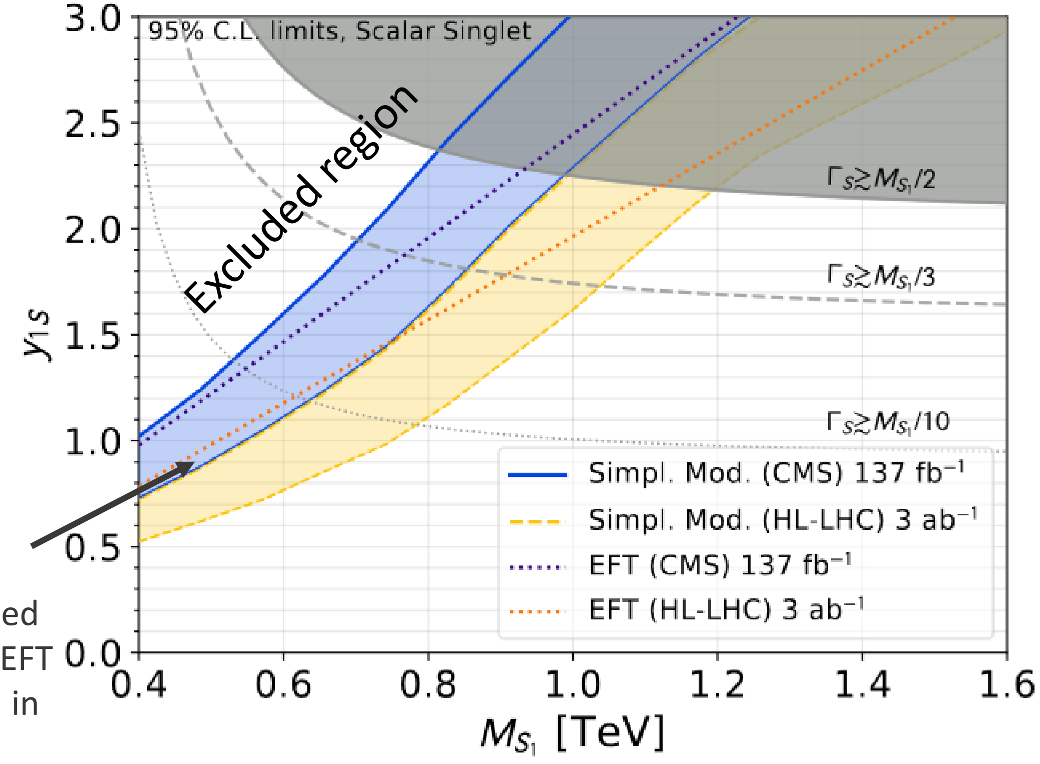
Results, singlet case

- Bands are from varying CS by factor of 2 (K factor 1 or 2)
- Note that the simplified approach quickly breaks down at large masses (width Γ_S too large)

LD, Fuks, Maltoni -- 2104.09512



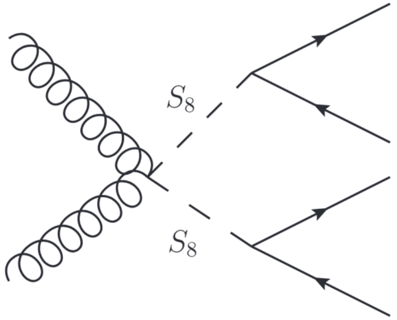
LD, Fuks, Maltoni -- 2104.09512



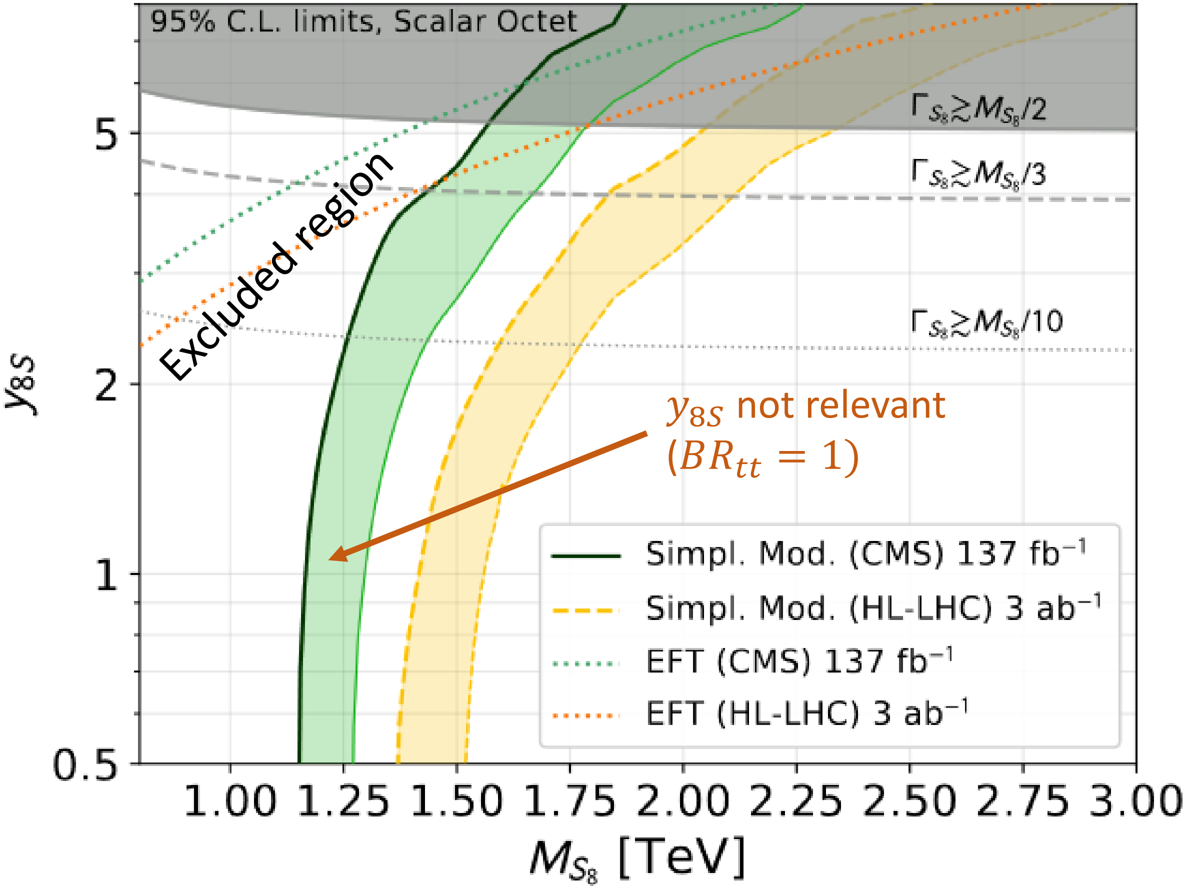
Fortuitious matching EFT/simplified model: the EFT is NOT valid in this range

Results, octet case

- Pair production leads to coupling-independent limit
- Small region at large masses with good EFT/simplified match

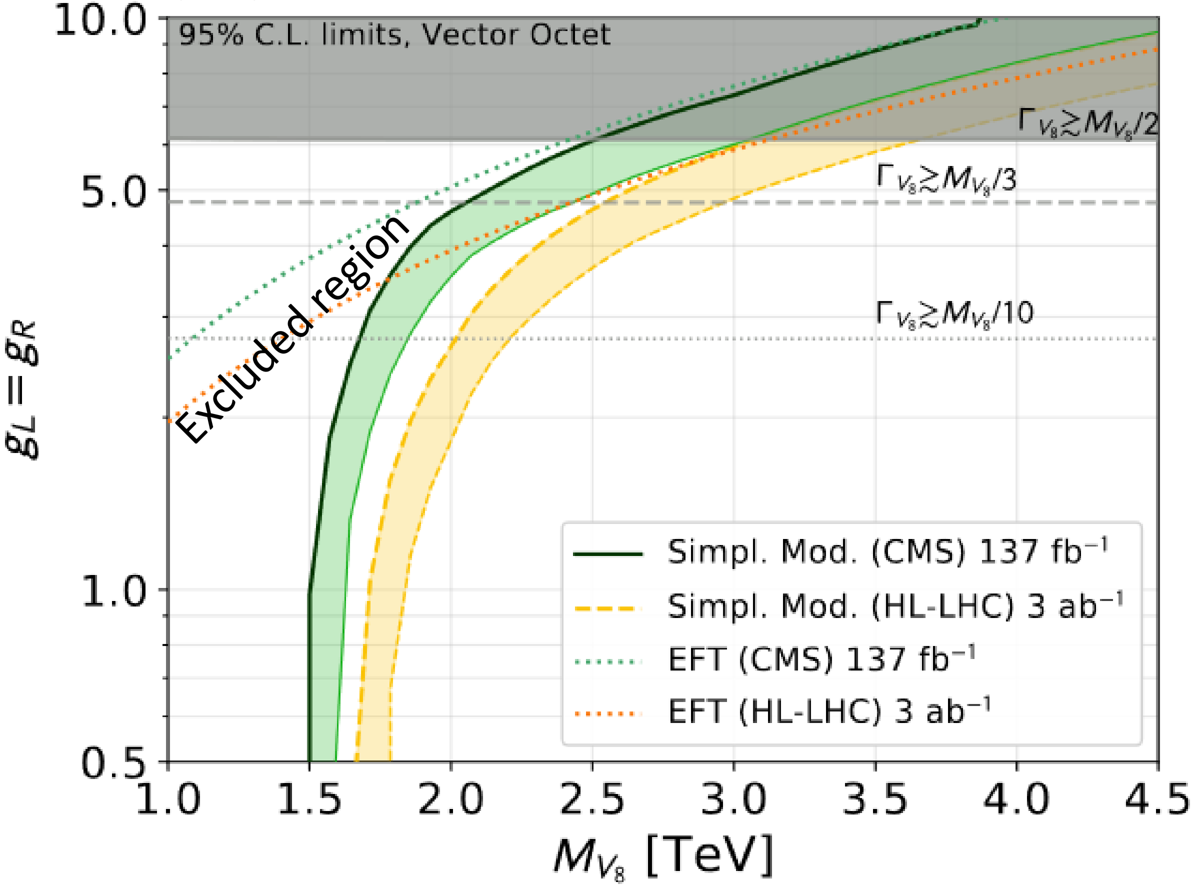


LD, Fuks, Maltoni -- 2104.09512



y_{8S} not relevant
$(BR_{tt} = 1)$

LD, Fuks, Maltoni -- 2104.09512



ML and top-philic state reconstruction

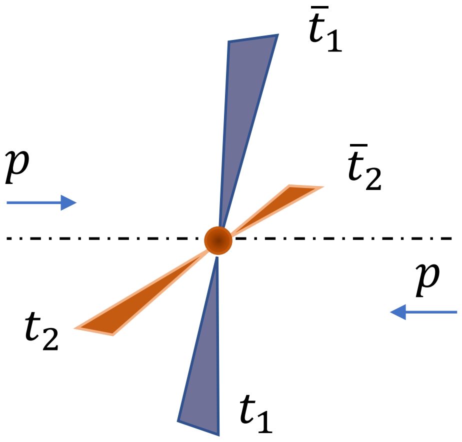
- In the previous plots, the limits around the TeV scale are dominated by our toy high H_T SR

Work in progress with O. Mattelaer, and B. Fuks and collaborators

- In general, we should be able to do much better by reconstructing the tops invariant mass and searching for the resonance

→ Leverage the large p_T from the X decays, and associate the opposite pairs to a resonance

→ Learn from di-tops searches



- At lower masses, several machine learning techniques are being investigated by theory groups

Atkinson et al. 2302.08281

→ Reconstruct properly the tops from the final states particles via GNN

→ Distinguish ttW from $tttt$ (Demixer algorithm, Bayesian probabilistic modelling)

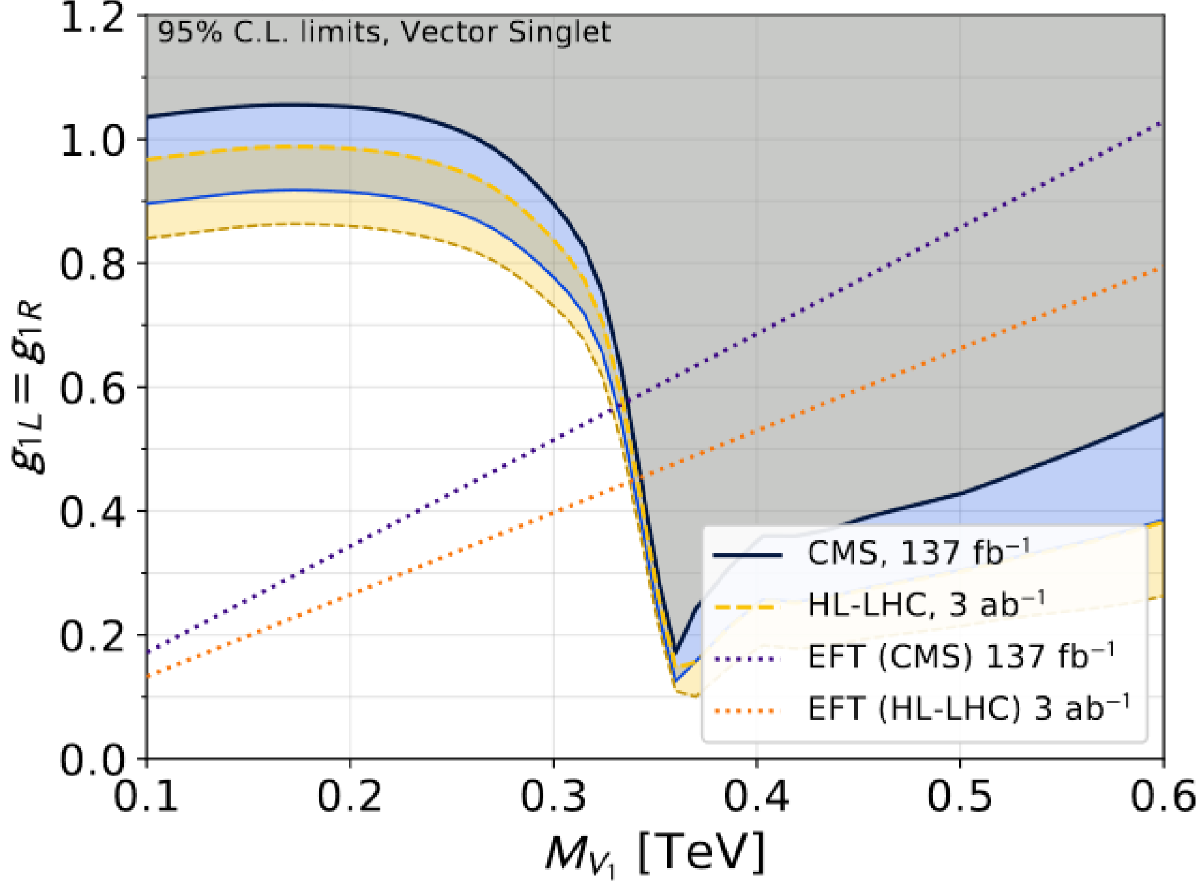
Alvarez et al. 1911.09699, 2107.00668

Comments on the "low masses" range

- When the top-philic particle is lighter than two top masses: no on-shell decay (to tops) available
- Situation closely mimics the existing SM processes
  - → Interference plays an important role
  - → Measurement gets close to the SM precision prediction (NP will become "systematics"-dominated at HL-LHC if no advance on theory side)

$$\sigma_{4t}^{\mathrm{SM}} = 11.97^{+2.15}_{-2.51}\ \mathrm{fb}$$

LD, Fuks, Maltoni -- 2104.09512

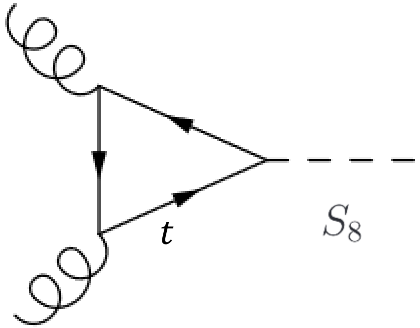


- Use another decay channel in ttX configuration ?
  - → With reconstruction of the $X \rightarrow \gamma\gamma, bb, \mu\mu, \tau\tau$ etc…

Loop processes at small masses

- With top-couplings only, loop-induced contribution can be important

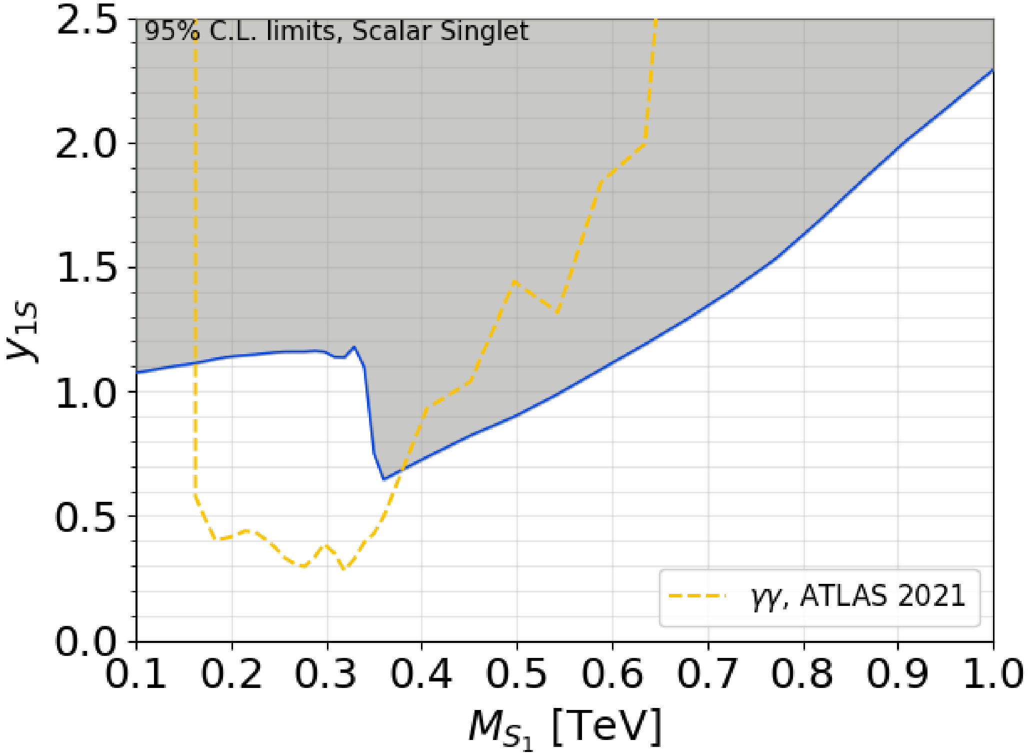
  → Similarly to the Higgs ggX and $\gamma\gamma X$ are loop-induced



- Very important in the light X, $m_X < 2\, m_t$

  → Only possible decay channels are via loop-induced couplings

  → Di-photon final states decays are not too supressed



Work in progress with A. Darricau and G. Cacciapaglia

A range of different analysis to include e.g. ATLAS 2205.01835, 2211.04172, 2102.13405

Conclusion

Conclusion

- Top-philic particles are a relatively common feature of several well-motivated SM-extensions
- Fast experimental progresses on $t\bar{t}t\bar{t}$ searches
  - → Experiments are still statistically limited
- A focus on "on-shell" NP production (resonant opportunities) is critical to properly leverage the capability of both LHC and HL-LHC
  - →Illustrated by high-Ht analysis approach, m_{tttt} tail, etc …
  - →New dedicated analysis strategies probably required
- Still a pretty active field on the theory side !
  - → We are getting a better control over the SMEFT predictions for this process and its range of validity (NLO estimates are going to be long run effort)
  - → New ideas tested to get the best out of the $t\bar{t}t\bar{t}$ states for NP-dedicated analysis